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RESEARCH PAPER

Time Prediction Models and Cost Evaluation of Cut-To-Length (CTL) Harvesting Method in a Mountainous Forest

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Abstract Time equations are derived for felling with chainsaw, skidding with cable wheeled skidder, loading with grapple hydraulic loader and trucking of logs within a cut-to-length harvesting method. The continuous time study method was applied to collect data for felling, skidding, loading and a transportation model. Multiple regression analysis via SPSS software was applied to develop the time models. Felling time was found to be highly dependent on diameter at breast height. Skidding distance, winching distance, slope of the trail and piece volume were significant variables for the skidding time prediction model. The loading time model was developed considering piece volume. Transportation distance and load volume were used as independent variables in modeling the transportation time. The net production of felling was estimated at 12 trees/h (56.65 m^3/h). The net production rates for skidding, loading and traveling averaged 18.51, 41.90 and 3.32 m^3/h respectively. The total cost of harvesting from stand to mill was estimated 19.70 €/m^3. The skidding phase was the most expensive component of the cut-to-length method. The bucking and delimbing components were less costly than the other logging phases. The results of this study can be used for harvesting planning and productivity optimization.

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Introduction

Components of harvesting systems include felling, bucking, yarding, loading, transportation, unloading and road construction (Conway 1982). The cut-to-length (CTL) harvesting method in Northern Iran consists of following components: felling, delimbing and bucking, skidding, loading and transportation to the sawmill. Discrimination of the effective factors in each stage and developing their corresponding time models helps forest managers to choose wisely the method of extracting wood, and efficiently manage the process of harvesting operations. One of the common ways to evaluate a harvesting system is time study and cost-production evaluation. This paper reports cost and time prediction models for motor manual felling, skidding with cable wheeled skidder, loading with a hydraulic grapple loader and transportation using a truck, which are the components of a typical ground skidding system in most developing countries.

Previous studies have reported that tree diameter (dbh), ground slope and species of tree influence felling time in motor manually felling (e.g. Boe 1963; Kluender and Stokes 1996; Hartsough et al. 2001; Wang et al. 2004; Ghaffariyan and Sobhany 2007; Nikouy et al. 2008). Most of statistical studies on skidding operations indicated that skidding distance, piece size, load volume, winching distance and slope of the trail impact strongly on the production of this step of the logging process (Sobhany and Stuart 1991; Naghdi 1996; Abeli 1996; Daxner et al. 1997; Egan and Baumgras 2003; Sabo and Porsinsky 2005; Naghdi 2004; Zecic et al. 2005).

For loading with a hydraulic loader the most important variable affecting the productivity is volume of load (Boe 1963; Lanford et al. 1990; Azizi 2001; Akay et al. 2004). Secondary transportation (transportation from forest to mill) has been studied by many researchers (Asikainen 1995, 1998; Moll and Copstead 1996; Lückge and Weber 1998; Sikanen et al. 2005; Linko 2006; Kühmaier et al. 2007; Fenz and Stampfer 2007; Nurminen and Heinonen 2007; Möller and Nielsen 2007). The effective variables have been transport distance, load volume and load weight. Eghtesadi (1991) and Naghdi (2004) developed transportation time models for trailers for two forest companies in the north of Iran (Mazandaran Wood and Paper Industries, and Neka Choob Company respectively). However, there has been no study to evaluate the CTL method in the ground-based skidding system using log trucks in this area. This paper presents production, cost and time models for felling, skidding, loading, and log transport to give forest managers more complete information for the ground-based logging system.

Case Study Area and Logging Method

The research was carried out in the second district of Naav forest Shafaroud watershed management area, northern Iran, with an altitude range of 1,030 and

1,250 m, and average annual precipitation of 1,000 mm. The forest was uneven-aged and its main species was beech (*Fagus orientalis*). The area of the compartment was 69 ha, and the maximum and average gradients were 80 and 35 %, respectively. The trees were felled, delimbed and bucked to the assortment by motor chain saw. The logs were then skidded to the landing near the road side. The hydraulic loader was used to load the logs on the log trucks to be transported to the mill (Fig. 1).

A Stihl 090 chainsaw was used for felling. The felling team consisted of a chainsaw operator and his assistant. A Timberjack cable skidder, model 6BTA5.9 with 177 hp motor was used for uphill yarding. The rubber tyre skidder (Timberjack 450C) was equipped with an arch (a hard pan attached to the skidder for extracting the logs) and 50 m of cable were used for skidding. The skidding team consisted of operator, choker man and chainsaw operator. The type of loader used was Volvo BM4500, model TD706 with 14,500 kg weight and the truck model was Benz 2624.

Research Method

The silvicultural method was single or group selective cutting. Except for felling which is usually done in winter, other work component data were gathered in summer. Rainy weather could be an obstacle in skidding operation at any season. However, the productivity in summer is usually higher than in winter.

The *continuous time study* method was applied to collect the data for separate felling, skidding, loading and transportation models. The felling cycle was divided to five time elements: moving of the felling crew to the tree, deciding about the felling direction, under cut, back cut and delay. During each felling cycle, dbh, distance to the tree, slope of the trail to the tree and ground slope at the stump were measured. Felling time was considered as a function of these measured variables. A more conventional way of saying this would be that a multivariate population relationship was hypothesized, and multiple regression was used to fit and test a

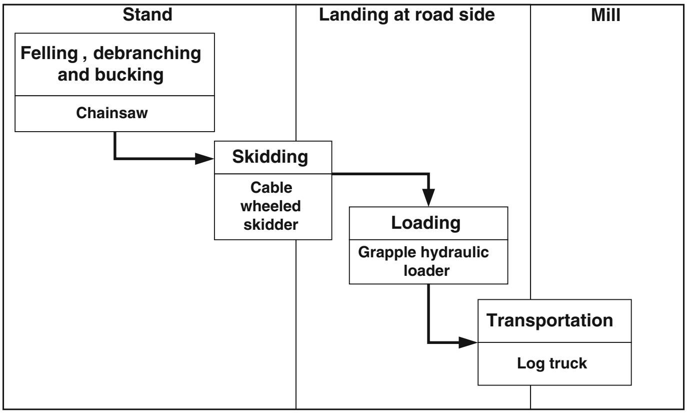

Fig. 1 Cut-to-length harvesting method in the study area (Naav District)

model based on sample data. The skidding working cycle included travel empty, establishing the skidder, releasing the cable, setting the choker, winching, travel loaded, opening the choker at the landing and piling the logs at the roadside.

The technical, personal and operational delays were recorded during the time study. It was hypothesized that the skidding time per cycle is a function of skidding distance, winching distance, slope of the trail and piece volume. The stepwise regression method, a combination of forward selection and backward elimination method, was used to develop a free delay (excluding downtime) skidding time prediction model. To evaluate the production of mechanical loading, the loading cycle was divided to four elements, namely selecting, grappling, loading and adjustment of the load on the truck. The delays were also timed and recorded. The piece size was measured as a variable affecting on the loading time. The loading phase was represented as a loading model. The traveling time for the loaded and empty components was considered as a function of traveling distance and load volume. Both two-variable and multiple regression analysis were applied using the SPSS software, to develop the time prediction model.

The cost for each phase of the CTL system was collected based on the contract of the Shafaroud Company. The data in the present study were based on the average forestry worker salary in the northern forest of Iran for year 2010. The workers may receive some premium and gratuity in the month.

For felling and skidding elements, 180 and 50 working cycles respectively were studied. The study design for the secondary transport phase included 24 working cycles for loading the logs, traveling to the mill, and unloading.

Results

The felling time prediction model

The time study yielded a production rate of 12 trees per hour (56.65 m^3/h) including free delay working time. The old stands in the study area consisted of very large trees (average DBH of 68 cm). Based on felling time measured during the time study, the production rate averaged 10 trees per hour. The felling time $F(t)$ model developed to predict the free delay time of felling using chainsaw in relation to log dbh, and resulting test statistics, were

$$F(t) = -1.582 + 0.099\,\mathrm{dbh},\ n = 180,\ R^2 = 0.62$$

Table 1 presents the analysis of the variance of this model, and reveals that the model is significant at the 1 % level. Felling time is found to be higher for larger diameter trees.

The time distribution of various elements of the time study on manual felling using chainsaw are: move to tree 12 %, reconnaissance 11 %, under cut 27 %, back cut 31 % and delay 19 %. Notably, the back cut has the highest share of the felling time, and delay times account for about one-fifth of total working time. Table 2 presents summary statistics of the parameters of the felling model.

Table 1 Results of one-way ANOVA for the felling model

Source of variation	Sum of squares	df	Mean square	F	Sig.
Regression	1,041.188	1	1,041.188	290.976	0.000
Residual	636.930	178	3.578		
Total	1,678.118	179			

Table 2 Descriptive statistics for felling model

Parameter	Minimum	Maximum	Mean
dbh (cm)	25	130	67.76
Distance between trees (m)	2	125.70	26.24
Cross slope (%)	5	69	40.83
Longitudinal slope (%)	−55	60	12.81
Felling net time (min.)	0.98	18.77	5.11

The skidding model

The average net and gross productions were 18.51 and 14.51 m^3/h respectively. Using stepwise regression the following model was estimated:

$$T = 13.027 + 0.127\ D_w + 0.035\ D_s - 0.847\ S + 0.551\ V, n = 50,\ R^2 = 0.64$$

where T = time of one cycle (min), D_w = Winching distance (m), D_s = Skidding distance (m), S = Degree of slope (%), V_1 = Load volume (m^3)

Increasing the winching distance, skidding distance, and load volume will increase the skidding time. However, increasing the slope decreases the working time for downhill skidding in this case study. The coefficient of determination (R^2) for this model is 0.64, which indicates that the model explains 64 % of the variation in the time of one skidding cycle. As indicated in Table 3, the model is significant at the 1 % level.

The variance inflation factors (VIF) for the parameters of the skidding model (Table 4) were computed to assure that the collinearity among the variables was not high.

Table 5 presents the share of the working element and delays to the total working time. Operational and personal delay was 22 % of total time, which is relatively

Table 3 Results of ANOVA for skidding model

Source of variation	Sum of squares	df	Mean square	F	Sig.
Regression	551.129	4	137.782	19.667	0.000
Residual	315.254	45	7.006		
Total	866.382	49			

Table 4 Confidence intervals and colinearity statistics for the variables of the skidding model

Coefficient	95% confidence interval for coefficient		Colinearity statistics	
	Lower limit	Upper limit	Tolerance	VIF
Constant	5.418	20.637		
Winching distance (m)	0.076	0.178	0.914	1.094
Skidding distance(m)	0.021	0.050	0.868	1.152
Slope (%)	−1.374	−.320	0.948	1.055
Load volume (m^3)	0.048	1.053	0.997	1.003

Table 5 Time distribution for skidding operation (% of total work time)

Travel empty	Estab-lishing	Cable release	Choker setting	Winching	Travel loaded	Choker opening	Pilling	Personal delay	Operational delay	Technical delay
16	3	8	8	8	21	4	10	10	12	0

Table 6 Descriptive statistics of skidding time study

Parameter	Minimum	Maximum	Average
Slope (%)	11	16	14
Winching distance (m)	2.1	78	22.89
Skidding distance (m)	100.4	323.4	211.56
Piece volume (m^3)	1.45	4.93	2.78
Free delay skidding cycle time (min.)	6.88	24.22	13.47
Gross skidding cycle time (min.)	6.88	40.28	17.18

high. The skidding crew did not have choker, and instead used the cable itself, resulting in excessive cable setting time. Table 6 presents the descriptive statistics for the skidding time study.

The loading model

The net and gross production rates for loading with a hydraulic loader averaged 41.9 and 35.06 m^3/h respectively. The inverse model was developed using the curve estimation regression method in SPSS. The significance level of the estimated model (Table 7) is less than 1 % which confirms the significance of the model.

$$L(t) - 23.297/V_p, n = 24, \; R^2 = 0.94$$

where $L(t)$ = loading time per cycle (min), and V_p = piece volume (m^3).

The model explains 94 % of the total variation of the dependent variable (loading time per cycle). Increasing the piece size will decrease the loading volume.

Table 8 presents the time distribution for the observed elements of loading time, and Table 9 presents the descriptive statistics of the loading time.

Table 7 Results of ANOVA for loading time model

Source of variation	Sum of squares	*df*	Mean square	*F*	Sig.
Regression	9,097.044	1	9,097.044	325.53	0.00
Residual	614.797	22	27.945		
Total	9,711.841	23			

Table 8 Time distribution for loading operation (% of total work time)

Selecting	Grappling	Loading	Adjusting	Operational delay	Technical delay	Personal delay
19	24	21	19	13	0	4

Table 9 Summary statistics of the parameters of loading model

Parameter	N	Minimum	Maximum	Mean
Piece volume (m^3)	23	0.71	2.37	1.38
Load volume (m^3)	23	10.22	16.65	14.02
Net loading time (min/cycle)	23	13.80	32.73	20.08
Gross loading time (min/cycle)	23	16.28	39.18	24

Table 10 Results of ANOVA for travel time model for truck

Source of variation	Sum of squares	*df*	Mean square	*F*	Sig.
Regression	3,465.271	2	1,732.636	21.87	0.00
Residual	1,584.468	20	79.223		
Total	5,049.739	22			

Traveling time model for transportation by truck

The average loaded and empty speeds of traveling were 29.02 and 37.32 km/h respectively. The net and gross production averaged at 3.32 and 2.94 m^3/h. The calculated speeds can be used to predict the net time of traveling depending on the transportation distance. The following estimated model shows the effects of hauling distance and load volume on traveling time of the skidder per each work cycle.

$$T(t) = -60.179 + 3.934\, D_t + 3.087\, V_l, n = 24,\ R^2 = 0.69$$

where $T(t)$ = time of loaded traveling (min), D_t = traveling distance (km), and V_l = load volume (m^3).

The travel time model explains 69 % of total variation of traveling time. The ANOVA table (Table 10) reveals that this model is significant at the 1 % level.

The VIF values for the parameters of the travel model shows that colinearity is not a problem in this model (Table 11).

Table 11 Confidence intervals and collinearity statistics for the variables of the travel model

Coefficient	95% confidence interval for coefficient		Collinearity statistics	
	Lower limit	Upper limit	Tolerance	VIF
Constant	−163.433	43.075		
Load volume	0.961	5.212	0.989	1.011
Distance	2.451	5.418	0.989	1.011

Table 12 Summary statistics for travel model with truck

Parameter	Minimum	Maximum	Mean
Travel loaded time (min.)	127	160	142.48
Travel empty time (min)	97	127	111
Distance (km)	66.50	73	68.72
Load volume (m^3)	10.22	16.65	14.02
Free delay travel time (min.)	227	280	253.47
Personal delay (min)	10	25	15.47
Operational delay(min.)	10	45	17.13
Technical delay (min.)	0	0	0
Gross travel time (min./cycle)	257	330	286.09

Table 13 Analysis of variance of unloading model

Source of variation	Sum of squares	*df*	Mean square	*F*	Sig.
Regression	0.345	1	0.345	12.180	0.002
Residual	0.624	22	0.028		
Total	0.969	23			

The distribution of times for traveling phase of transportation component is: travel empty 39 %, travel loaded 50 %, operational delay 6 %, technical delay 0 % and personal delay 5 %. The descriptive statistics of the time study for transport with truck are presented in Table 12.

Unloading with grapple hydraulic loader

The exponential model was fitted to the data to develop the unloading time prediction model.

$$U(t) = 9.284\ e^{0.038V_l},\ n = 24,\ R^2 = 0.356$$

where $U(t)$ = the Unloading time (min/truck) and V_l = the Load volume (m^3)

As indicated in Table 13, the relationship is significant at the 1 % level.

Table 14 Descriptive statistics of unloading model

Parameter	N	Minimum	Maximum	Mean	SD deviation
Load volume (m^3)	24	8.29	19.35	14.2805	3.22605
Unloading cycle time (min.)	24	10.93	23.50	16.2958	3.34812
Gross working time (min.)	24	10.93	37.87	18.6014	6.79163

Table 15 Summary of the cost for CTL system in Shafaroud Company

Component	Cost (€/m^3)
Felling	0.33
Bucking and delimbing	0.16
Skidding	8.10
Loading	3.01
Transportation	5.70
Unloading	2.40
Total	19.70

The shares of working elements of the unloading time study are: moving 16 %, grappling 40 %, unloading 17 %, stacking at year 15 % and operational delay 12 %. Table 14 includes the descriptive statistics of parameters of unloading time.

Operation costs

The cost of each component of the CTL system in the case study area is presented in the Table 15. The hourly machine cost included fixed cost, variable cost and labour cost which was estimated using a standard cost estimation method. The hourly cost of each machine was divided by its corresponding productivity to derive unit cost. The total cost is the sum of costs of each single machine. The total cost of the CTL system is 4.93 €/m^3 higher than that reported by Mousavi (2009) for the tree length system (about 14.77 €/m^3) of the Shafaroud Company. Processing the trees to the short logs in CTL system with increase the cost of bucking, skidding, loading and unloading as piece size has significant impact upon the productivity of each of the menthioned components.

The skidding phase was the most expensive component of the CTL method. The bucking and delimbing components were least costly compared to the other logging phases.

Discussion

This study aimed to develop the time prediction models for all components of the CTL harvesting method in northern Iran. The purpose was to construct models for each components of the harvesting system in a mountainous forest. The results and models are applicable for downhill skidding in areas with the similar working

conditions and equipment around the world. Furthermore, the results are valid with appropriate weather condition in summer season.

Tree diameter (dbh) was found to be the most important determinant of time consumption and productivity. In addition to the dbh, distance between trees was also found to influence productivity of felling operation. Tree diameter (dbh) was found to be the only variable significantly influencing felling time using chainsaw in the study area, which is consistent with the findings of Ghaffariyan and Sobhany (2007).

Productivity of processing, skidding and hauling will increase when using the long length method. Total unit cost of the long-log method in processing, skidding, loading and hauling is lower than under the short-log method, which is consistent with the findings of Mousavi (2009).

The skidding productivity in this case study depended on the load volume. Ghaffariyan et al. (2011) reported that increasing load volume will result in lower cost of extraction thus to reduce the extraction cost, it is necessary to plan use of harvesting equipment to work with maximum capacity. However, they suggested that increasing load volume may increase machine repair costs, an aspect which requires further investigation.

The delay time for all components of the logging system was found to be relatively high, and efficiency could be increased by reducing delay time. Operational delays in the management area (including waiting and stoppage time when the workers or machines are not available at the moment they are needed) were particularly high, suggesting that the logging in the area was poorly managed. The main reason might be the lack of cost-production analysis for various types of harvesting machines.

Conclusions

Tree diameter (dbh) was found to be the most influential factor affecting time consumption and productivity of felling while inter-tree distance also effects felling time consumption and productivity. The productivity of felling large diameter trees is higher than of felling trees with a small diameter. A large number of logs per cycle compensates for the lower volume in the short-log method in skidding.

Further investigation is needed of the bucking and delimbing time requirements using chainsaws. Future study can investigate the yield of the CTL harvesting system (Wiedemann and Ghaffariyan 2010). Also, other studies are needed to compare the tree-length and CTL harvesting methods in a uniform stand considering economic and environmental impacts on the soil and remaining stands.

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